Selection and Verification of Kenaf Fibres as an Alternative Friction Material Using Weighted Decision Matrix Method

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Abstract

Nowadays, natural fibres composites are widely investigated and acknowledged as materials which minimise carbon dioxide produced in all phases of their interaction with environment compared to glass fibres composites. However, the fibres selection is still based on economic factors and local availability rather than dependency on a systematic approach. Therefore, this paper suggests a study on how kenaf fibres is verified compared to other natural fibres that could potentially be used as an alternative source of friction material (FMs) using the Weighted Decision Matrix (WDM) approach. The method of selection is to consider the impact on the environment and human health. An exhaustive review of potential natural fibres and friction materials is presented and suggested for future development direction. The result shows that WDM method verifies the suggested suitability of kenaf fibres.

Keywords: Natural fibres; Kenaf fibres; Weighted Decision Matrix; Materials Design

1. Introduction

In order to reduce weight, there are two important methods. One of these methods is to redesign the selected parts to optimise their structure. The other method is to replace traditional materials with lightweight materials such as aluminium alloy, polymer, or composites [1, 2]. Following the Life Cycle Analysis (LCA) in recent years, natural fibres composites are widely investigated and acknowledged as materials which minimise carbon dioxide produced in all phases of their interaction with environment (pre-production, production, service, end-of-life) compared to glass fibres composites which minimize noise production [3-5].

The advantage of using natural fibres is the potential that it could lead to a weight reduction of 10–30% [6] due to low density that causes economical fuel consumption. This enhances the possibility for manufacturers to consider to expanding the use of natural fibres in their new products.

With regards to recycling concerns, manufacturers are driven by European Union regulations (ELV) to consider the environmental impacts of their production and possibly shift from petroleum-based to agro-based materials [7, 8]. However, currently conventional reinforcing materials used, such as glass fibres, carbon fibres, and aramid fibres, are not biodegradable, possess poor recycling properties, are health risks if inhaled, are of high density and effect high energy consumption in the preparation of its products, and cost more to be manufactured [9].

Recycling automotive interior parts is the most challenging phase due to the current petro-based polymer composite structures which leave only two disposal options of either landfills or burning. A possible solution for this problem is to make interior parts using one single polymer or biodegradable materials which are less harmful to the environment versus petro-based polymer composites that are found to improve the mechanical properties of biodegradable plastics while reducing the overall costs of the prepared materials [10].

Research demonstrates that the use of natural fibres, such as kenaf, ramie, flax, hemp, and cotton for automotive composite applications, has many advantages both technically and economically [11]. These bio-based composites enhance mechanical strength and acoustic performance, possess less weight, lower production cost, their auto interior parts are biodegradable, but currently information on actual performance using natural fibres is limited with respect to FMs (lining shoes).

Natural plant-based lignocelluloses fibres are very attractive reinforcing materials [12]. The major drawbacks of natural fibres compared to synthetic fibres are their non-uniformity, variety of dimensions, and their mechanical properties [13]. High moisture absorption that could cause instability in mechanical properties and loss of dimensional stability is another disadvantage [14]. Most composites based on polymeric fibres swell due to moisture absorption that leads to alterations in weights and dimensions of the composite produced, as well as in strengths and stiffness.

Another limitation of natural (plant) fibres is the limited research conducted on thermal stability. They undergo degradation when processed beyond 200°C when the choice of using polymer matrix is included [15]. Disadvantages of natural fibres reinforcement generally solved by fibres surface alkaline treatment or matrix modifications by the removal of the carboxyl group [14, 16-20]. The result finds alkaline treatment improves the mechanical properties of natural fibres, especially in relation to their strength and stiffness [21-23].

In spite of the growing interest for these materials, fibres selection is still based on economic factors and local availability rather than dependency on a systematic approach. This study shows the potential selection of natural fibres using data collected and verification via the Weighted Decision Matrix (WDM) approach with respect to FM properties and design specifications.

From the earlier studies of Mustafa et al. [24], selection of possible alternative friction materials is developed using CES Edupack. The present study shows how to verify kenaf fibres that could potentially be used as an alternative friction material using the WDM approach. This paper is structured according to the relation of potential natural fibres selection; requirements for automotive materials; collected material properties data; justification and verification by the WDM method [25].

2. Kenaf fibres

Kenaf, as shown in Figure 1 [26], is the stems of plants, genus hibiscus, and the family of malvaceae called hibiscus cannabinus. Advantages of kenaf is less water required to grow due to matured cycle of kenaf about 150 to 180 days with an average yield of 1700kg/ha [27]. Kenaf are cultivated in some countries such as Bangladesh, Australia, Thailand, parts of Africa, Indonesia and Malaysia. Kenaf is a plant that can be grown under a wide range of weather conditions, for example, it grows to more than 3m within 3 months, even in moderate ambient conditions with stem diameters of 25-51mm [28].

-Figure 1-

Kenaf plant is composed of many useful components (e.g., stalks, leaves, and seeds) and within each of these, there are various usable portions (e.g., fibres and fibres strands, proteins, oils, and allelopathic chemicals) [29]. Recently, there are increasing new crop of kenaf fibres in the United States which shows good potential for usage as reinforcement in composite products. The latest innovation in decortications which separates core from the bast fibres combined fibres shortages, have gained the interest of utilising kenaf as a fibres source [30].

Kenaf fibres also have a potential as reinforced fibres in thermosets and thermoplastic composites which resulted low density, non-abrasiveness during processing, high specific mechanical properties and biodegradability [31]. So, combining kenaf fibres with the thermoset material provides a strategy for producing advanced thermoset composites that take advantage of the properties of the types of material [32]. Kenaf fibres categorized as natural fibres which are biodegradable, an environmentally friendly crop and have been found to be important source fibres for composites and other industrial applications [31, 33].

3. Automotive friction materials

Friction materials in an automotive brake system function by converting the vehicle's kinetic energy into heat energy. Currently two types of automotive brake friction that available for use for lightweight car materials that are semi-metallic and non-asbestos organic [34-35]. Generally, an automotive brake FM (i.e. for brake shoes and brake pads) is fabricated with a combination of several materials of unique complex compositions that are known as binders, reinforcing fibres, fillers, and friction modifiers [36-37]. Several studies indicate and suggest desirable performance for automotive brake friction materials includes stability and a high friction coefficient (μ), reduced vibration (judder) and noise, being environmentally friendly, resistant to heat, wear, fade, oxidisation, thermal properties, cracking, water, oil, and does not damage the brake disc, with the capability of being manufactured at reasonable cost [34-36, 38].

Asbestos is known as a major constituent used in the composition of FMs, but is a proven human carcinogenic. Therefore, asbestos is banned by the Environmental Protection Agency (EPA) since 1992 (39), and drives researchers' increasing interest in developing of potential NAO materials with safer alternatives [34, 40-44]. Based on the collected data, many researchers chose natural fibres [45] as alternatives to overcoming sustainable issues of being environment friendly, fully biodegradable, abundantly available, renewable, cheap and have low density but become disadvantageous in wet conditions due to high hydroxyl content of cellulose that potentially absorbs water that generally effects mechanical properties of the composite in wet conditions [46] so modification needs to be performed to overcome this problem for effectiveness and functional NOA produced [47].

4. Materials selection

Referring to Figure 2, performance and effectiveness of a designed product are affected by selecting the best option of capability to provide the necessary performance in service and processing method. Therefore caution must be exercised when selecting potential materials selected to prevent leading to excessive life-cycle cost and failure to produce. Generally, materials that are selected based on performance characteristics with yields to bear the given load or force applied with minimum or better properties and better characteristics such as less cost and business consideration, result in less impact on the environment and a better life cycle [36].

-Figure 2-

4.1 Requirement of the materials in automotive

Ghassemieh [48] suggested that materials applied in the automotive industry must pass several criteria before being approved. The criteria suggest alignment with regulations and legislation for the environment, safety concerns and meet some of customers' requirements. There are many conflicting factors that require consideration, therefore optimising a balanced solution that meet before the design is proven successful for service.

a. Lightweight

Minimises greenhouse gas production and improves fuel efficiency for vehicles. For every 10% of weight reduced from a vehicle, total weight of improved fuel economy is recorded at 7%, leading to a kilogram of weight reduction in a vehicle per 20kg of carbon dioxide reduced [49].

b. Cost

Cost is one of the most important variables which analyses and determines whether any new material selected can be included in vehicle components. Cost consists of three variables that are cost of raw material, manufacturing cost, and cost to design and test.

c. Safety and Crashworthiness

The "crashworthiness" of the structure in vehicle is the ability to withstand and survive impact energy applied for the crash test [50].

d. Recycling and life-cycle considerations

Protecting the environment increases awareness of pollution and reduced impact of CO_2 emissions', with 'recycling' being considerations before inclusion into the vehicle components.

5. Natural fibres selection requirements

Automotive brake friction materials are a favourable function on various crucial roles such as safety performance, including stopping distance and time, resistance to wear between disc and lining pad, and vibration with minimised noise production when operating [51]. It is strong enough to absorb and withstand brake torque even at high temperatures and various environmental conditions [52]. Effective performances with high resistance follow life-cycles as desirable characteristics for prolonged periods of maintenance to reduce cost and change more frequently. Heat produced during braking and for normal operation record temperature on the rotor range from 200ºC -250ºC, and 370ºC for the front wheel disc pads [53-55] of passenger cars. Several studies show typical pressure applied, ranging from 0 to 4MPa and where safety modern brake systems are designed with the capability to withstand up to 10MPa [56].

Literature reviews indicate that to develop an effective and functional friction material, a balance of key factors is necessary to satisfy yield of acceptable performance, cost and environmental friendliness. It is also proven that the right composition of friction material formulation and weight percentages of elements or materials included per total weight can significantly affect changes on physical, mechanical and chemical properties of friction materials developed [57-58]. Earlier researchers conclude that there is no simple correlation between friction and wear properties of friction material, with the physical and mechanical properties [59-61].

With the same objective, Chan and Stachpwiak [34] found numerical studies for friction materials developed through trial and error, coupled with previous experiences of the manufacturer for optimisation and evaluation performance of friction materials investigated using mathematical methods, such as grey relational analysis [62] and the single-criterion extension evaluation method [63]. The relationship between correct combination and composition of materials and particle sizes proves to enhance the tribological performance of the braking interface [64-65]. All the criterion and specifications are detailed by Mustafa et al. [24] following all the consideration when CES Edupack selection material approach is suggested by Ashby and Cebon [66].

6. Justification and verification natural fibres with WDM

A direct example is used for the WDM selection approach to choose alternative materials that demonstrate data found by Mustafa et al, 2014 [24], including collected materials data from CES universal material properties database and collected reviews. WDM method is where all the matrix decision is summed to ‘1’ by Eq. (1) shown below and suggested by George and Schmit [25]. *n* is the number of evaluations and *W* is the weighting factor. WDM methods are approached by determining: the weighting factor with respect to performance and specifications of FMs; objective tree; and matrix decision table to select the most suited natural fibres.

$$\sum_{i=1}^{n} W_i = 1.0 \quad \text{and} \quad 0 \le W_i \le 1 \qquad (1)$$

There are steps recommended when following this method. Starting with identifying which criteria is the most important to be achieved based on the design requirements to determine which weighting factor is used. The details illustrated in Figure 3 include environmental effects, cost, performance and lightweight material selected. Sub-categories for environmental impacts include safe disposal, and non-toxic materials with less impact on the environment. Sub-categories for performances are followed by strength, including stiffness, and functionality at various temperatures and conditions.

-Figure 3-

Figure 4 shows the completed objective tree after applying the weighting factor for each criterion. Total sum of matrix values at each level follows Eq. (1) with the higher matrix showing the most considerable change. For example, $O_{11}+O_{12}+O_{13}+O_{14}=1.0$ and $O_{111}+O_{112}+O_{113}=1.0$, repeated for each level. For this study, the environmental, cost, performance and lightweight properties are all of equal standing, so the same weight factor are suggested for these categories. For sub-categories such as performance, these characteristics are desired performances for automotive FMs to be functional when produced and applied to the brake system. It is also environmentally friendly by producing less energy and CO_2 with respect to eco-aware properties.

-Figure 4-

After step 1 and 2 are finalised, the decision matrix table can be constructed as shown in Table 1 where all the criteria are being analysed and calculated in order to identify which material performs the best. The weight factors of 11-point scales are used to solve this selection. Weight factor is derived through the objective tree which shows an example of strength: $O_{131}=0.25 \times 0.25 \times 1.0 = 0.0625$, while scores indicate the desired outcome for this study suggests automotive FMs [38]. The rating for each concept of each design criterion is obtained by multiplying the score and weight factor. Thus, the rating for strength is 0.0625 x 7 = 0.4375.

Based on Table 1, the WDM indicates that the most suitable material is kenaf fibres which can be used on eco-aware lightweight automotive friction materials. According to the result, the material also exhibit promising properties of being the lightest, cheapest and highest reduction percentage of embodied energy and CO_2 compared to asbestos and other natural fibres.

-Table 1-

In Malaysia, kenaf is a new type of agriculture crop which can produce fibres of excellent strength and has great potential to be used as a raw component for non-woven material [67]. Advantages of kenaf are that they are easy to grow within a short time, have high productivity, possess pest control, and have high adaptability to weather and soil.

Suggested from collected reviews regarding kenaf fibres; it needs treatment before it is fabricated for surface treatment resulting in higher strength and flexibility compared to untreated natural fibres. Figure 5 shows the untreated and treated kenaf fibres that will be used in this study. Kenaf also acknowledges the capability to absorb CO_2 at a significantly high rate; exhibits low density; is non-abrasiveness during processing; has high specific mechanical properties (comparable to jute, ramie, and asbestos), and is biodegradability. Recently, kenaf uses raw material alternatives to the wood in pulp and paper industries, in the textile industry [68-72] could be utilised as reinforcement material for polymeric composites as replacement for fibres glass. The disadvantage of these natural fibres is a high moisture absorption which may be overcome by imbedding the fibres in polyolefin matrices.

-Figure 5-

Based on Edeerozey et al. [73], the increase in tensile strength using kenaf fibres treated with NaOH is due to the improvement in the interfacial bonding and additional sites of mechanical interlocking which promotes more resin/fibres interpenetration at the surface [74]. Surface adhesion characteristics are encouraged by removing natural and artificial impurities, thereby producing a rough surface topography [75]. It has been reported that alkali treatment leads to fibres fibrillation, breaking down of fibres bundles into smaller fibres, increasing the effective surface area available for contact within the matrix [76].

Magnificent results are recorded for treated composites, in terms of interfacial adhesion between kenaf filler and the polymer matrix. Recently, Maleic Anhydride (MA) grafted Polypropylene (MAPP) used widely in kenaf–PP systems. Interestingly, Sanadi et al reported a significant improvement in terms of tensile and flexural properties of kenaf– PP composite, when incorporating it with MAPP as a coupling agent [77]. They found that coupled composites, showing a superior tensile strength of up to 74MPa, shows a contrary trend where the uncoupled composites demonstrate some very interesting behaviour, with tensile modulus higher than that of any coupled systems at identical fibres loadings. The use of kenaf fibres reinforces composites which can help to generate jobs in both rural and urban areas in addition to helping reduce waste for a healthier environment.

7. Conclusions

Selection for an alternative material to asbestos is included as an automotive friction material, performed using the WDM method based on a formulated design and its requirements. Through all of the criteria and the constraints, kenaf fibres are identified as being the most suitable material, which pass all the design requirements. The results show promising potential for kenaf fibres by capability on eco-aware with lower impact to the environment, is the lightest and the cheapest compared to other natural fibres.

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Figures

Figure 1

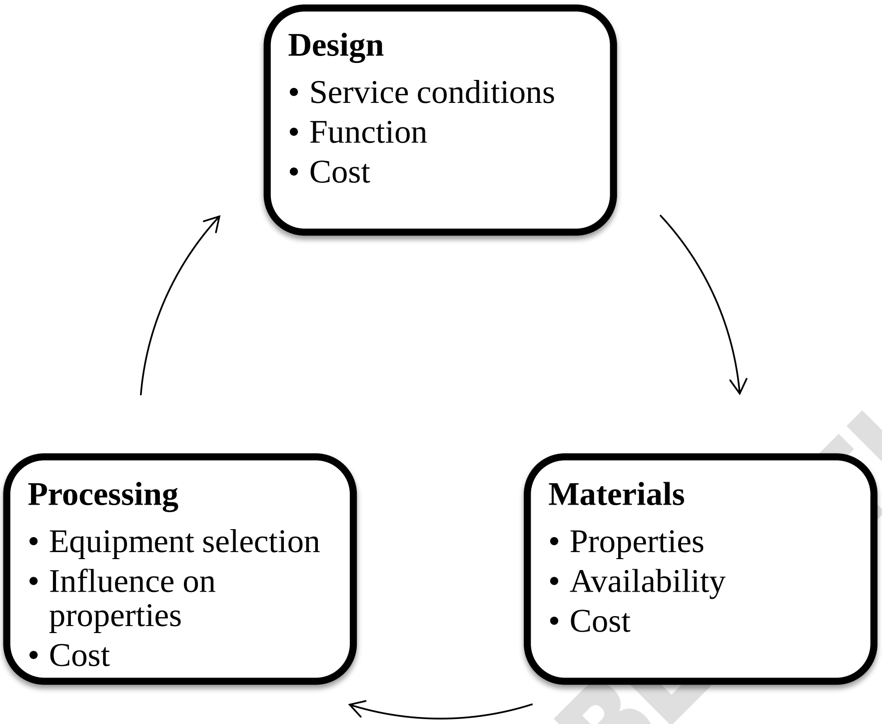

Design
• Service conditions
• Function
• Cost
Processing
• Equipment selection
• Influence on properties
• Cost
Materials
• Properties
• Availability
• Cost

Figure 2

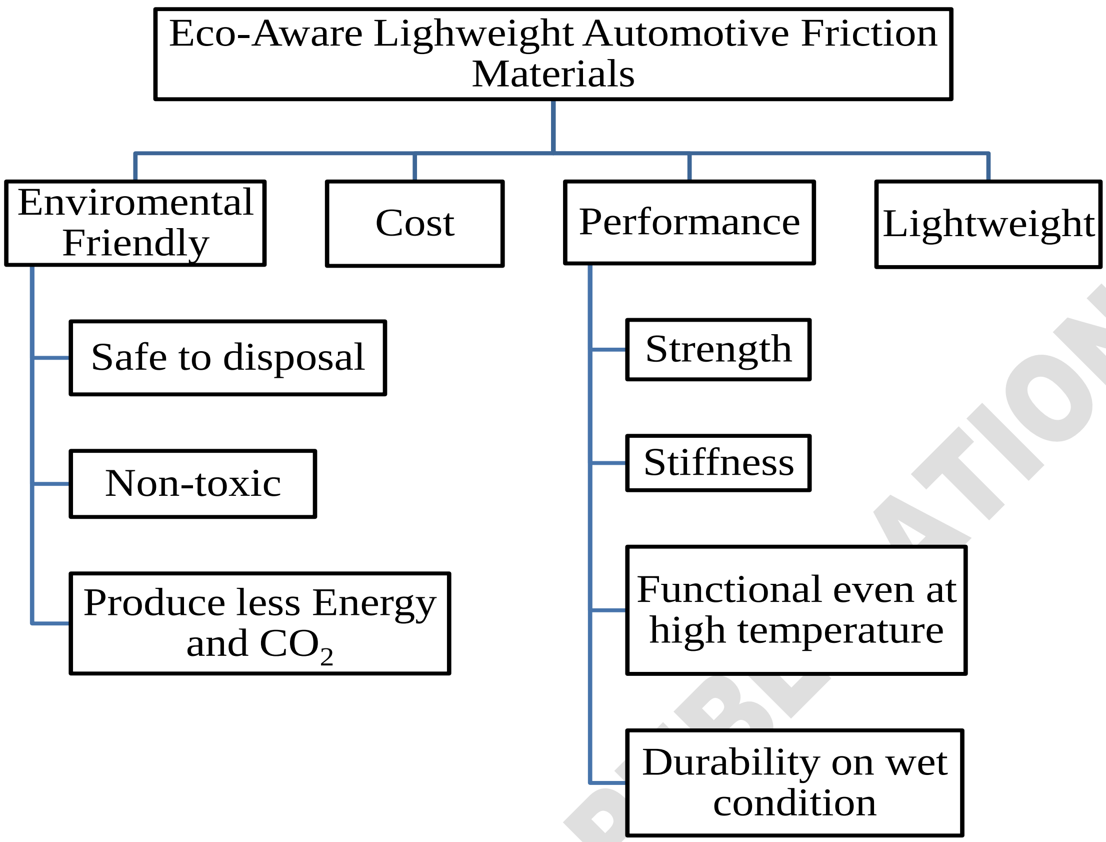
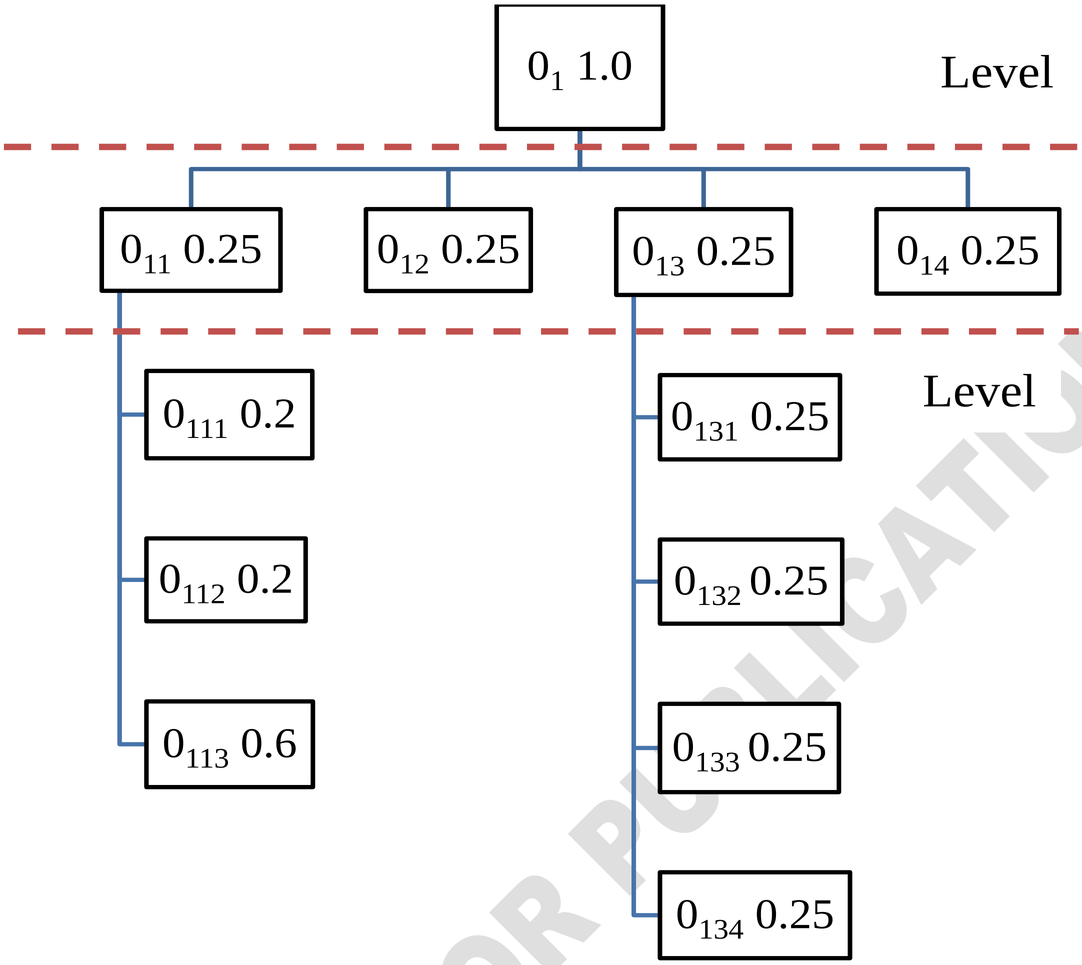

Eco-Aware Lighweight Automotive Friction Materials
Enviromental Friendly
Cost
Performance
Lightweight
Safe to disposal
Non-toxic
Produce less Energy and CO_2
Strength
Stiffness
Functional even at high temperature
Durability on wet condition

Figure 3



0₁ 1.0
Level
0₁₁ 0.25
0₁₂ 0.25
0₁₃ 0.25
0₁₄ 0.25
Level
0₁₁₁ 0.2
0₁₁₂ 0.2
0₁₁₃ 0.6
0₁₃₁ 0.25
0₁₃₂ 0.25
0₁₃₃ 0.25
0₁₃₄ 0.25

Figure 4


Untreated kenaf bast fibres
Treated kenaf bast fibres
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 5

Table

Table 1

Design criterion	Weight Factor	Units	Kenaf fibres			Jute fibres			Ramie fibres			Asbestos		
			Value	**Score**	**Rating**	**Value**	**Score**	**Rating**	**Value**	**Score**	**Rating**	**Value**	**Score**	**Rating**
Strength	0.0625	MPa	361	7	0.4375	277	7	0.4375	469	8	0.5	3140	10	0.625
Stiffness	0.0625	GPa	27.2	7	0.4375	27.9	7	0.4375	88.7	8	0.5	165	9	0.5625
Density	0.25	kgm^{-3}	1190	10	2.5	1400	8	2	1500	7	1.75	2500	4	1
Maximum service temperature	0.0625	^{o}C	410	5	0.3125	410	5	0.3125	410	5	0.3125	914	9	0.5625
Durability with water	0.0625		Acceptable	8	0.5	Acceptable	8	0.5	Excellent	9	0.5625	Excellent	9	0.5625
Toxicity	0.05		Non-toxic	10	0.5	Non-toxic	10	0.5	Non-toxic	10	0.5	Toxic	0	0
Price	0.25	MYR/kg	1.15	9	2.25	2.26	5	1.25	6.04	1	0.25	5.78	3	0.75
Energy and CO_2 footprint	0.15	% change	-39, -44	9	1.35	-31, -37	9	1.35	-40, -40	9	1.35	datum	1	0.15
Safe for disposal	0.05		Yes	9	0.45	Yes	9	0.45	Yes	9	0.45	No	1	0.05
Total					**8.7375**			7.2375			6.175			4.2625

Indicator: Totally useless solution 0, Very inadequate solution 1, Weak solution 2, Poor solution 3, Tolerable solution 4, Satisfactory solution 5, Good solution with a few drawbacks 6, Good solution 7, Very good solution 8, Excellent 9, Ideal solution 10. (Source: CES universal material properties database).

Figure captions

Figure 1 Kenaf (hibiscus cannabinus) [26]

Figure 2 Relationship between materials selection and design

Figure 3 Objective tree

Figure 4 Objective trees with determined weight factor

Figure 5 Photo of untreated and treated kenaf bast fibres

Table caption

Table 1 Weighted Decision Matrix for eco-aware lightweight automotive friction materials